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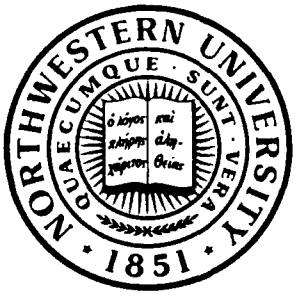

EVANSTON, ILLINOIS

"MATERIALS CAN BE STRESSED OUT TOO!"

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ABSTRACT

"Locked in" or *residual stresses* occur almost always in making and using materials, from computer chips and dental fillings to tanker hulls, pipe lines and air craft. These stresses can sometimes improve the life of a manufactured item, but can also lead to catastrophic failure.

Introduction:

As early as the 2nd century, and perhaps much earlier, Chinese artisans manufactured bronze discs, 15-20 cm in diameter and 4 -7 mm thick, that were flat and polished on one side, and had a pattern in relief, typically several mm high, cast on the other side (1,2). When such a disc is illuminated on the flat face, the reflection shows the pattern of the relief on the other side (figure 1). According to one explanation that dates back to 11th century, this effect may be due to non-uniform thermal contraction of the disc upon quenching from high temperature. During quenching, regions with different thicknesses cool at different rates. This means that the regions that cool the fastest "shrink" more than the slower cooling regions and "pull" on them, causing distortions on the flat side. These distortions mimic the pattern of the relief, making it "visible" through the brass. Another interpretation is that the design outline was punched on one side, and then the back-side polished. Such deformation also causes a residual stress pattern similar to the quenching, as we will discuss later and, again, makes the pattern visible from the backside. To our knowledge, this is the first deliberate use of residual stresses and strains. Of course, the ancient Chinese did not call this phenomenon a result of residual stresses, preferring, rather, the more picturesque names "mirrors that let the light through" or "magic mirrors". Considering the age, this was an apt description for the invisible forces that make a relief visible through solid brass.

These same invisible forces are also quite wide-spread in our modern world. They can be found in almost all manufactured objects, from computer chips, dental fillings, engine crankshafts, railroad bridge struts to oil tanker hulls. Unfortunately, residual stresses do not always cause good "magic". They add algebraically to the loads that a given object undergoes in service and can cause failure, sometimes with catastrophic consequences, if not properly taken into account. For example, residual stresses caused failure of girders in the Lafayette short bridge over the Mississippi river in St. Paul in 1975, forcing the closing of the bridge (3). Very large residual stresses can also exist in welded parts. These stresses can cause spontaneous, sometimes violent, cracks in the structures. Such cracks can be initiated by a sudden drop in temperature or due to a small impact. However, they sometimes occur while the part is in storage, sitting on a shelf. Welding stresses must be taken into account in the design of all welded structures, from oil platforms to railroad tracks (much of the rail system in the U.S. is

welded together).

Residual stresses, if correctly controlled, can also significantly increase service life of manufactured parts. For example, automotive valve springs are routinely treated by an operation called "peening" which imparts compressive residual stresses in the surface material (4). (In peening a surface is bombarded with small round metal or glass beads, or sand.) Springs treated in this manner last ten times longer than unpeened springs. In a similar fashion, ship propellers that are shot-peened show greater resistance to corrosion in the salt water (5). These effects are solely due to the modification of surface residual stresses. Since most failures initiate at the surface, the type (tensile or compressive) and magnitude of the surface stresses are very important. If the surface is in compression, any cracks that form due to corrosion, local deformation in use, etc., do not "grow" as quickly in subsequent use; they are literally forced closed by the compressive stress field. If, on the other hand, the surface stresses are tensile, they enhance crack growth and aid the destruction of the object. We may also note here that, it is not enough to know the residual stress state at the beginning of any mechanical process or duty cycle. All processes or duty cycles can alter the stress state and degrade beneficial stresses or even replace them with harmful ones. Thus, one needs to monitor the stress states through the manufacturing and use cycles.

Another significant effect of residual stresses is change in the dimensions and shape of objects that contain them. They cause bending and warpage in machined parts, putting an effective limit on how thin a part can be that must remain flat after machining (such as grinding, cutting, etc.). Thermal residual stresses can cause warpage and fracture in printed circuit cards and in the microelectronic chips that are used on such cards. On the other hand, controlled residual stresses can bend parts to very exact and uniform curvature with minimum tooling. This is done, for example, in peen-forming, where large fuselage and wing sections for aircraft are bombarded with glass beads over their surface areas. The residual stresses that form bend the sections to a specific curvature uniformly over the entire surface(6). Furthermore, this operation causes beneficial compressive residual stresses at the surface, eliminating a separate production step. However, if the residual stresses are altered during service due to applied loads, the shape will also change. Thus, the design and implementation of

such structures require careful stress analysis.

From these examples, we can see that residual stresses are quite important in all aspects of manufacture and use. Thus, we need to understand the origins of residual stresses, consider ways of measuring them and assess their effects on mechanical strength and reliability.

Definitions:

These days, we define residual stresses as "those self-equilibrated stresses that exist in a body that has no external influences acting upon it"(7). This definition emphasizes the two important aspects of residual stresses:

1. They exist in "free-standing" bodies that have no external forces, torques or moments acting on them.

2. They are completely equilibrated within the body; that is to say, if one part of the body is being pulled in tension, another part of the body must be squeezed in compression.

We can illustrate these concepts with a simple system consisting of a compression spring of length L_0, a bolt that is longer than L_0 and a nut (figure 2). Let us now slip the spring over the bolt, and then start tightening the nut. There will be no stresses in the system up to and including the point where the nut just touches the top of the spring. At this point, the distance between the nut and the bolt is equal to the rest length of our spring, "L_0". If we keep tightening the nut further, the spring becomes shorter than L_0, and it will be in compression. If the distance between the nut and the bolt cap is L_f, the force in the spring will be:

$$F = K(L_f - L_0). \qquad (1)$$

Here K is the spring constant for our spring and $(L_f - L_0)$ is the "constrained length" that is contained by the displacement of the nut. As we can see from this equation, the force is directly proportional to this "constrained length".

The force given by equation (1) is transmitted to the bolt through the nut and

the bolt cap where it is balanced by the reaction of the material in the bolt. This reaction can be described by the stress (σ) in the bolt body:

$$\sigma = - \frac{F}{A} \tag{2}$$

where A is the cross sectional area of the bolt. The negative sign indicates that the force in the bolt is equal but opposite to that in the spring. Since the spring is in compression, the bolt is in tension. These tensile stresses cause a strain (&epsilon.) in the bolt given by:

$$\epsilon = \frac{\sigma}{E} = \frac{- K(L_f - L_0)}{E} \tag{3}$$

Here E, the Young's modulus, is a fundamental material constant that describes the proportionality between applied stress (load) and observed strain (elongation) in a given material.

The nut-compression spring-bolt system satisfies all requirements of our definition. There are residual stress fields within the assembly even though there are no external forces acting on it, and the forces within the assembly are completely balanced (with the bolt under tension and the spring under compression). This assembly also illustrates the cardinal requirement for the formation of residual stresses. Namely, one part of a given body must, for what-ever reason, undergo a a permanent change in dimensions. In the spring assembly, this change is the "shrinking" distance between the bolt cap and the nut. In the Chinese "magic mirrors", unequal thermal shrinkage between sections of different thicknesses causes the residual stress fields. Any other process that can cause dimensional change, such as deformation, phase transformations, defect incorporation, etc., can also cause residual stresses. However, if such (permanent) dimension change is uniform (homogeneous) across the entire body, no stress fields will form. In our spring assembly the distance between the nut and the bolt changes from L_0 to L_f permanently while the dimensional change in the spring is elastic* (recoverable). If the deformation in both components of the system were

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*If the bolt were cut in half, the spring would again attain its original length L_0. However, if we remove the spring and put the cut edges of the bolt together, the distance between the nut and the bolt cap would still remain at L_f.

permanent, there would be no residual stresses. This would be so if, for example, the spring were crushed permanently to L_f. In this case, if the bolt were cut in half, the spring would still remain at length L_f, which is equal to the distance between the nut and the bolt cap.

The dimensions over which the stress field is constant is also an important parameter. Depending on the magnitude of these distances, we may define two different types of residual stresses. In the above example, the stresses are constant over continuous large dimensions. For example, the spring has the same (compressive) stress state over its entire volume. The (tensile) stress state in the bolt is also constant over the volume of the bolt. Such stresses are called "macrostresses". Macrostresses are balanced between continuous macroscopic volumes of the body. There are also micro residual stress fields. These are balanced between microscopic regions within a macroscopic volume. As a simple example, consider a porous stone soaked in water such that each pore is completely full of liquid. We, thus, have a two phase material, with one phase being the water and the other stone. Let us now have a phase transformation in one of the phases: If the temperature of the stone drops below 0°C, the water within each pore will freeze and expand, pushing against the pore walls. The pore walls will, thus, be placed under tension, while their reaction will place the ice contained within under compression. The stress field is completely balanced between the stone forming the pore-walls and the ice within them for each pore. Here the stress state will change over pore dimensions, alternating every time a boundary between water and stone is crossed. Overall, the magnitude of the stresses in the stone and the ice depend on the fraction of volume "f" they occupy. Balancing of the forces requires that:

$$\sigma_{stone} f_{stone} \quad \sigma_{ice} f_{ice} = 0 \tag{4}$$

Here σ denotes the stress in the phase noted in the subscript. Since &sigma. and "f" are interdependent, the phase with the smaller volume fraction (the minor phase) can have large micro stresses. These stresses can be quite important in technological processes. For example, microstresses form in multi-phase materials in response to deformation, temperature changes, etc. Since tensile microstresses can initiate cracking at phase boundaries, or in the phases themselves, these stresses must also be taken into account during manufacture.

On the other hand, compressive microstresses in the deformation zone ahead of a crack tip retard crack propagation in ductile materials (8).

Examples of Residual Stress Fields

Let us now follow a part through production and discuss the manufacturing operations that the part undergoes and the residual stress changes that are associated with each step. To start with, we assume that we have a slab of material, e.g., steel, that has no residual stresses. The part we will manufacture will be first machined from this slab. This involves removal of the excess material through operations such as cutting, turning (on a lathe), milling (on a milling machine) and grinding (to give it a good surface finish). Then, we will heat treat this part in an oven to harden it, and then, if the residual stress profile warrants it, we will further treat it to obtain the desired residual surface stresses.

Let us start the operation with the machining steps where we remove material excess to the shape of our object from the slab. Machining operations such as grinding, turning, etc., are essentially chip removal operations where the tool breaks small chips of material from the workpiece. In traditional operations, the chip formation and removal are accomplished by mechanically straining a small local area of the workpiece above the fracture limit through the relative motions of the tool and the workpiece. During this process, the tool will cause plastic (permanent) deformation in the material surrounding the chip. This surrounding material remains after the chip is removed and forms part of the machined surface. Thus, the machined surface will have plastic strains (permanent deformation) after the operation. This deformation will cause machining stresses in the part. The process can be visualized in the following manner (figure 3). Imagine the near surface region to be detached from the main body (bulk) of the object and machined separately. The impact of the tool during the chip forming will cause permanent (plastic) deformation only in this layer. The length of this layer will then become $L_0 + \delta L$, where L_0 is the initial length and δL is the length change due to machining. To rejoin the surface and the bulk such that the boundaries match (or to keep them together to start with), we have to squeeze the surface regions and elongate the bulk. After joining, the surface will, thus, be in compression, the bulk will be in tension, and the final length of the part will be greater than L_0 but less than $L_0 + \delta L$. To balance the forces in these layers, the ratio of the stresses in

the surface and the bulk must be equal to the thickness ratio of the layers; that is:

$$\frac{\sigma_1}{\sigma_0} = \frac{t_0}{t_1} \tag{5}$$

Where σ_0, σ_1 are the stresses and t_0, t_1 are the thicknesses of the bulk and the surface layers respectively. For most cases, t_1 is much smaller than t_0. Thus, there will be significant stresses in the surface layers but negligible stresses in the bulk*. Both the sign and magnitude of the surface stresses are determined by the sign and magnitude of the length change δL caused by machining. If the surface is elongated; ($\delta L > 0$), the surface stresses are compressive. If on the other hand the surface is shortened ($\delta L < 0$), the surface stresses are tensile. A given operation can cause either tensile or compressive residual stresses. The sign and the magnitude of the stress field is determined by the machining conditions such as cooling, feed rate, depth of cut, etc., rather than the type of the operation. For example, in case of surface grinding (figure 4), the following conditions have been observed (9).

1. The residual stress parallel to the grinding direction is directed opposite to the horizontal direction of feed into the grinding wheel in the last grinding pass.

2. Increasing depth of cut increases the normal residual stresses.

3. Cooling decreases the tensile residual stresses in a medium carbon steel but *increases* them in unalloyed iron (Armco iron).

Thus, a wide range of stresses, beneficial or detrimental can exist in the machined surfaces of the workpiece.

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* The stress distribution caused by one sided machining discussed above is not symmetric with respect to the center of the part and will cause bending. Such bending is negligible for thick specimens, where the layer affected by machining is much thinner than the total thickness of the specimen. As the specimen gets thinner, some finite curvature due to bending can be observed. This effect will be treated later in the text.

Assume, at this point, that we have finished machining our part. It has the desired shape and has grinding residual stresses in the surface layers. We can now heat-treat it to obtain desirable material characteristics. For example, the hardness of steel can be doubled or tripled by various methods of heat-treatment. In fact, once a part is fully hardened, it can no longer be easily machined; most cutting tools can not penetrate it. Heat treatment usually involves subjecting the part to certain temperatures. Let us now place our part in an oven and heat it up to the heat-treatment temperature. If the heating is very rapid, large temperature differences may exist between different regions of the part. At temperature T, the length of any section of our part is given by:

$$L_T = L_0 \{1 + \alpha(T - T_r)\} \tag{6}$$

where α is the thermal expansion coefficient of the material, and T_r is room temperature. Consider two sections adjacent to each other that are at the same length L_0 at room temperature. If there are large thermal gradients during heating, they will have different temperatures T_a, T_b, and thus, will try to expand to different final lengths. The constrained length between sections "a" and "b" will be proportional to the temperature difference:

$$L_a - L_b = L_0 \alpha(T_a - T_b) \tag{7}$$

Of course, such constrained length causes the formation of a residual stress field. These stresses are termed thermal residual stresses. In single phase materials, thermal stresses are proportional to the temperature difference between the two sections. Such stresses can be quite large! For iron based materials, the thermal stress is 3.5 MPa, (500 Psi) per degree of temperature difference. Since the yield point of mild steel (the stress required for initiation of plastic deformation) is about 500 MPa at room temperature and falls with increasing temperature, a temperature difference of 150°C between adjoining regions is enough to cause yielding. Furthermore, the thermal stress adds onto the machining stresses, and the total stress, coupled with the low material yield strength associated with a high temperature, can cause plastic flow (permanent deformation) even if the temperature gradients within the part are smaller. Such deformation changes the "constrained" length and, thus, relaxes the stress field. If the material is heated very slowly, such that all regions are at the same

temperature at all times, thermal stresses will be minimized for "homogeneous" materials If, on the other hand, the object has two or more parts made of different materials with different expansion coefficients, (α_0, α_1), etc., there will be thermal stresses even if all parts are at the same temperature. In this case the constrained length, and hence the thermal stress will be proportional to the difference of thermal expansion coefficients between any two sections.

Once the part reaches the prescribed temperature and is heat-treated, it must be cooled back to room temperature. In this case, similar arguments apply. For example, if the surface layers cool faster, they will try to shrink more. The interior, however, is hotter and will resist the shrinkage. Thus, a thermal stress field is set up. If the thermal stresses are high enough and cause permanent elongation in the surface layers (location A in figure 5-a), then, once the system reaches room temperature, this permanent elongation will be constrained by the interior (which suffered no plastic deformation and cools down to the same length it originally was). Thus, the surface will be in compression after the heat-treatment, which is the desirable stress state for most applications.

Heat treatment does not always produce "good" compressive stresses at the surface. If the material undergoes a phase transformation, where the crystal structure of the material changes, the stresses from this transformation also need to be taken into account. For example, in hardening steels, the soft austenite phase transforms on cooling into the hard martensite phase. However, the specific volume of martensite is larger than that of the austenite, and thus, dimensional changes occur upon the phase transformation. Such dimensional changes also produce residual stresses: Consider the cooling curve shown in figure 5-b. At point A, the surface regions reach the transition temperature and transform into martensite. This transformation is accompanied by expansion. The interior layers, composed of low strength austenite, deform plastically to partially accommodate this change. At B, the interior reaches the phase transformation temperature and transforms to martensite, expanding in the process. Since the surface is also high-strength martensite, the surface can not elongate in plastic flow to accommodate this expansion. The surface undergoes elastic expansion and, thus, is placed under tension. These stresses will persist unchanged during further cooling to room temperature (point C), if excessive thermal gradients do not occur between the surface and interior regions. Consequently, the finished part will

have tensile residual stresses at the surface which can cause crack initiation and propagation as noted earlier. To eliminate these stresses, stress relief annealing at moderate temperatures is often employed. In this procedure, the part is heated slowly to a temperature where local yielding relaxes the residual stresses. It is then cooled just as slowly to prevent further stresses from being formed.

Another way of changing the surface stress state from tensile to compressive is shot-peening. Each impact causes a little dimple in the metal normal to the surface and the material in the dimple is displaced in the plane of the surface. This causes local elongation of the material under each impact. Since the part receives thousands of impacts over its entire area, the total surface layer elongates permanently, and is placed under compression by the bulk material. Of course, this process will not work if the surface is hardened to the point where the shot can not deform it at all. In such a case, using higher velocity shot may cause flow in the surface layers, but may also cause cracking.

Up to this point, our discussion treated stresses that were constant over large volumes, such as surface or bulk layers, namely the macro stresses. This means that we implicitly assumed a single phase material. If, on the other hand, the material is multi-phase, the above operations will also cause a micro stress field For example, if we shot-peen a two-phase material, where one of the phases is weaker, each phase in the surface layer will elongate differently, with the weaker phase having more deformation which will be constrained by the stronger phase (figure 6). This interphase constraint will cause tensile micro-stresses in the stronger phase and compressive micro-stresses in the weaker phase. At the same time, the surface layer will also have compressive macro stresses due to the constraints from the bulk layers. The total stress in a given phase at the surface will be the sum of the macrostress plus the micro stress for that phase. Since the relative magnitude of the microstresses are proportional to the ratio of the volume fractions of the phases, the microstress component can be the dominant term in the total stress in the minor phase. That is, even if the macrostress component is compressive, a given phase may have very low compressive stresses or, in some cases, tensile residual stresses depending on its volume fraction. Such a material would be susceptible to cracking in that phase or at the phase boundaries, which could, after repeated cycles, cause failure.

So far, our discussion has been concerned mainly with metals. However, residual stresses are present in all materials. The type of the stress field, on the other hand, depends on the material properties. For example, most ceramic materials are very brittle and show little plastic flow before fracture. Thus, conventional modes of stress formation, such as elongation of the surface layers through plastic flow are difficult but not impossible. Large stresses can develop on grinding aluminum oxide, for example (10). Also, martensitic transformations are observed in some ceramic materials (such as zirconium dioxide) and one can use the transformation stresses to strengthen such materials (11). The transformation in these materials can be initiated by applying a force to the ceramic rather than heat-treating as discussed earlier. Thus, transformation can be initiated by the stresses surrounding a crack tip or by machining stresses. For example, if the surface of a ceramic containing ZrO_2 is ground, the force from the grinding wheel causes martensitic transformation in the ZrO_2 particles, which try to expand. This expansion is limited to the surface layers which see the maximum effect of the grinding wheel. Thus, the bulk material constrains the surface layers, putting them under compression and substantially increasing th fracture toughness of the material. Residual stress levels as high as 1GPa has been reported in such materials! On a micro scale, the stress field in front of the tip of a propagating crack can also cause transformation in the ceramic, placing the material into compression and deflecting or arresting the crack.

Methods of Measuring Residual Stresses:

In view of their importance, it is not surprising that there has been a continuing interest in developing methods for measuring residual stresses. There are a variety of methods that can be used for this purpose. However, none of the methods meet all the requirements that the "ideal" method should have. Such a method should be universally applicable to all materials, be non-destructive, measure macro and micro stresses at all depths in all locations, etc. In what follows, we will review the current methods in the light of these requirements.

Mechanical Methods of Residual Stress Determination

The mechanical methods of residual stress determination measure deflections and/or the changes in dimensions that occur when the residual stress profile changes. In some of these methods, the residual stress profile is changed deliberately by cutting or drilling out a part of the object. In others, the bending (curvature) of the part is measured after each processing step, and then the stress associated with that operation calculated. This "curvature method" is the basis of all mechanical stress methods. Thus, we will discuss it in some detail.

Let us first analyze the curvature caused by residual stresses. We have remarked previously that such curvature is utilized in the manufacture of aircraft fuselages. Another area also affected by residual stresses and the associated curvature is the microelectronics industry(12). We will use an example from this area.

Let us start with a bare silicon wafer upon which we want to manufacture computer chips. This wafer is simply a thin disk of Si, and it forms a base for the chips. On this base, we can form the devices (such as transistors, diodes, etc.,) by various methods (such as doping). These devices are, then, connected together by depositing lines of conductive material (such as aluminum) on the wafer surface. Because of the large number of devices, a large number of interconnections are required between various points. Thus, there can be multiple layers of such "metallization". The lines in these metallization layers are prevented from electrical shorting by "passivation layers". Polymeric materials such as polyimides or ceramic layers such as silicon nitride or silicon dioxide are used for this application. A simplified cross section of a chip with these different layers is shown in figure 7. All of these layers may have different thermal expansion coefficients and, thus, may cause residual stresses in the wafer during production. However, all of these layers must register perfectly on a very small scale. If the wafer curves in an uncontrolled or uncompensated manner after each step, registration of the next level can be quite difficult, if not impossible. In other cases, where the wafer is constrained during evaporation to ensure proper registration, such stresses can cause breakage during or after manufacture.

To analyze the stresses in such devices, let us use a model system, consisting of the Si wafer with a single "blanket" polyimide film covering one of its surfaces. We can manufacture such a system by "spinning on" a layer of

polyamic acid (which is quite fluid) on the wafer. This is accomplished by depositing the fluid on a rapidly spinning wafer. If the fluid volume is correct, all of the wafer surface will be uniformly coated. We then cure the polyamic acid at elevated temperature and, thus, transform it into a solid continuous film covering one surface of the wafer.

During cure, after solidification, the diameter of the polyimide film and that of the silicon will be equal (at the cure temperature). That is, $D_{Si} = D_{PI} = D_T$. Here, D_T is related to the diameter of silicon at room temperature D_0 through the thermal expansion equation:

$$D_T = D_0(1 + \alpha_{Si}\Delta T) \tag{8}$$

$$\Delta T = T - T_R$$

Upon cooling down to room temperature, the situation changes. Let us now assume that we can separate the polyimide film from the wafer at the cure temperature and cool them separately to room temperature. In this case, the silicon would shrink back to its rest diameter D_0. The polyimide film, on the other hand, has a different thermal expansion coefficient, α_{PI}, and would shrink back to a different diameter at room temperature. This diameter is given by:

$$(D_{PI})_0 = D_T\,(1 - \alpha_{PI}\Delta\, T) \tag{9}$$

Consequently, at room temperature, the difference in the diameters of the silicon and the polyimide film is:

$$(D_{PI})_0 - D_0 = D_0\,(\alpha_{PI} - \alpha_{Si})\,\Delta T \tag{10}$$

Because α_{PI} is much larger than α_{Si}, (21×10^{-6} vs. 2.8×10^{-6} per °C), the polyimide would contract much more than the Si wafer. Residual stresses arise since the two substances are bonded together and mutually constrain each other from reaching their respective diameters. This effect can be visualized in the following way: Take a cured film of polyimide of diameter $(D_{PI})_0$ and a silicon wafer of diameter D_0, and try to match the boundaries at a final diameter $D_{Si\text{-}PI}$ (figure 8). We can do this by applying tension to the film and compression to the

Si wafer. Once the boundaries match, let us glue the surface between the film and the wafer and then release the applied forces. At this point, we can represent the effect of the wafer on the film by a tensile force applied at the middle plane of the film and the effect of the film on the wafer by a compressive force applied at the middle point of the wafer. This force distribution, on the other hand, is not symmetric with respect to the center of the wafer and will cause some bending in the system. Taking the bending moment around the middle plane (where this moment is simply the product of the force and the distance between the application point of the force and the point we are taking the moment at):

$$M = F\frac{(t_{Si} + t_{P1})}{2} \tag{11}$$

Because of this moment, the wafer will bend into a spherical shell with a characteristic radius of curvature R that is proportional to M. But M is proportional to F, which, in turn is proportional to the residual stresses in the coated wafer. Thus, if we measure R we can calculate the residual stresses in the system. This was first done by Stoney in 1909 (12) when he calculated the stresses in metallic films deposited by electrolysis. Stoney showed that the stress in the film is related to the thicknesses of the film and the substrate and to the elastic constants of the substrate. His equation was extended by Timoshenko in 1923 (13) to cover the deflection of bi-metallic thermostats. This extended Stoney formula is still in use today and it is given by:

$$\sigma_{P1} = \frac{E}{(1-\nu)}\frac{t_0^2}{6Rt_1} \tag{12}$$

Here t_0, t_1 are the thicknesses of the wafer and film, E, ν are Young's modulus and Poisson's ratio of the wafer and R is the measured deflection. We can see from this equation that small radii of curvature indicates high stress. In semiconductor processing, some operations can cause a 5" diameter wafer to bend with a radius of 3 feet. That is, if one could attach 22 such wafers end to end, one would form a circle!

To apply the Stoney formula correctly, we must know the geometry of the part we are analyzing. If the layers making up the structure and their thicknesses are not known, application of the Stoney formula can cause large errors in the calcu-

lated stress. Consider the case where both faces of the Si are coated with the same thickness polyimide. The geometry is shown in figure (9). In this case, we have complete symmetry with respect to the center of the silicon and the structure will be subjected to bending moments M_1, M_2, from each side, that are equal in magnitude but opposite in sign. Thus, the total bending moment will be zero and the specimen will stay flat. Such a specimen would would yield a radius of curvature of infinity and the Stoney formula would yield zero stress. The stress on the Si is, however, twice that of one sided plating. We can see this by etching away the polyimide on either side. The remaining material will bend to the same radius of curvature as one sided plating (figure 9-d)!

This removal of material, and the monitoring of deflections or displacements arising from such removal operations, form the basis of layer removal and hole drilling techniques for stress determination (14, 15). In the hole drilling technique, the surface of a piece is instrumented with electric strain gages, then a hole is drilled within the area being monitored. Since the stresses within the removed volume are destroyed, some stress relaxation takes place which causes strains and, thus, changes in the dimensions of the remaining material. These displacements are measured by the strain gages. One can then calculate the stress state in the object before the drilling operation. The method requires careful attention to detail. One has to make sure that no new stresses are introduced by the material removal operation. Furthermore, measurements close to the drilled hole positions should not be used to avoid the stress concentration effects associated with the holes. For these reasons, the preferred method of material removal is usually chemical etching. In this method, the surface layer of the material is subjected to chemical attack and removed slowly. One has to take care that a layer of uniform thickness is removed. Then, if one measures the radius of curvature of the specimen as a function of thickness removed, one can calculate the initial residual stress profile in the part as a function of depth. This method usually gives good results. However, it is slow and not all materials can be chemically polished. Furthermore, micro stresses can not be measured by mechanical methods since changes in the dimensions of the individual phases can not be measured. All stresses measured from mechanical methods are macro-stresses.

Non-Destructive Stress Determination Methods

The "destructive" nature of the mechanical methods of stress determination is a serious disadvantage. They can not be applied to parts in use; nobody wants to drill into a bridge support girder with it supporting the traffic. Furthermore, these methods can not be used with expensive or one-of-a-kind parts. Various non-destructive stress determination techniques have been developed to address these problems.

A technique receiving great interest at the moment is based on acoustic wave propagation (16). We give here a qualitative introduction to this method. The velocity of a wave in a solid is relatively easy to measure using simple, portable equipment. velocity depends upon the square root of the elastic constant (B);

$$V = K\sqrt{B} \tag{13}$$

In the elastic region, stress and strain are proportional:

$$\sigma = B\,\epsilon \tag{14}$$

But actually, there are higher order elastic constants:

$$\sigma = B\epsilon + C\,\epsilon^2 + D\epsilon^3 + \ldots\ldots \tag{15}$$

Therefore, taking the first two terms of (14), a better approximation is:

$$\sigma \equiv (B + C\epsilon)\epsilon = B'\epsilon \tag{16}$$

Consequently, the velocity of a wave can be written as:

$$V = K\sqrt{B'} = K\sqrt{B} + C\epsilon. \tag{17}$$

The wave velocity depends on the state of strain, ϵ, in the material, and hence on the residual stresses. Unfortunately, the distribution of the phases can present effects that, so far, have prevented general use of this technique. Similar detrimental effects are also observed in single phase materials with preferred orientation (texture). So far, most of the use of this technique has been for untextured

single-phase materials under uniaxial loading (that is when the stresses are along a single axis only). However, progress is being made (17-18).

Another stress measuring method is associated with the Barkhausen "noise" in magnetic materials, produced when magnetic domains are moved by a field close to the material. The noise is sensitive to the stress fields in the material since the fields affect the ease of rotation of the domains (19). The measuring equipment is simple and portable. However, the technique is limited to magnetic ferrous (iron-based) alloys. Furthermore, the noise signal saturates around 500 MPa (70,000 psi) in either tension or compression. Above this value, the method is most useful (after calibration) for determining the sign of the stress.

Acoustic and magnetic stress determination methods we reviewed above are *indirect methods*. In both cases, stress is deduced from non-strain quantities. Direct methods, on the other hand, measure displacements and then calculate strains and stresses using equations of elasticity. Diffraction methods are direct methods. They measure displacements on an atomic scale using the spacing between planes of atoms as a strain gauge. There are two diffraction methods in use for stress determination. One uses x-rays. It is called the x-ray stress determination method. The other method uses neutrons. The same theory is applicable to both cases. Since the x-ray method enjoys much wider usage, we will treat this method in some detail and comment on the neutron method where necessary.

Let us first discuss a few *fundamentals of diffraction*. When a crystalline structure is irradiated with monochromatic x-rays of wavelength λ, constructive interference occurs at specific angles θ, where Bragg's law of diffraction;

$$\lambda = 2\, d \sin\theta \qquad (18)$$

is satisfied. Here "d" is the spacing of atomic planes parallel to the surface, shown in figure (10). Thus, if we irradiate the specimen with x-rays and then scan around it with a detector, at certain angles we will have peaks in the scattered intensity. From these angles, we can calculate the plane spacing d if we know λ. These scans are usually carried out on machines called diffractometers, the same instruments used in determining crystal structures, or to identify unknown

powders.

Let us now apply a compressive stress, σ, to the crystal along the x direction (figure 11). This stress will cause Poisson expansion along the z direction, which will also change the atomic plane spacing "d". Thus, the angular position of the x-ray peak will change. From this peak position, "d" can be calculated using Bragg's law. Then, if we know the unstressed lattice spacing, we can calculate the strain in the direction of the surface normal from:

$$\epsilon = \frac{d - d_0}{d_0} \tag{19}$$

The stress can, then, be calculated from equations of elasticity.

The simple procedure described above is the basis for stress measurement with x-rays (7). Of course, the actual situation is more complicated. For example, if the specimen is polycrystalline, that is, if it is made up of many single crystals with different orientations, diffraction occurs only from the crystals (grains) that have their atomic planes parallel to the surface. If the material is under compression, the plane spacing in these grains will be larger than the unstressed plane spacing. If the spacing is now tilted with respect to the incoming beam (figure 12), new grains diffract where the orientation of the diffraction planes has a component perpendicular to the stress direction. The result is that, with increasing ψ tilt, the interplanar spacing decreases. This property of polycrystalline specimens enables us to measure displacements, and, thus, strains, at various orientations to the surface. Consequently, multi-axial stress states can be determined uniquely. Theoretical analysis can predict the variation of d with the square of the sine of the tilt angle ψ. Figure (13) shows the types of d vs. $\sin^2\psi$ curves observed in practice and the stress states associated with them.

X-ray diffraction techniques have a number of restrictions dictated by the physics of diffraction. First of all, the material must be crystalline. Amorphous materials like most polymers or glasses can not be analyzed by this method directly. Secondly, X-rays are strongly absorbed by most materials, which causes diffraction to occur from a very shallow surface layer (20 microns or so in thickness). Thus, the strain/stress data calculated only applies to this layer.

This effect, in fact, is beneficial where steep strain gradients occur in the surface layers. However, if stresses below the surface are of interest, either removal of the top material by etching, or neutrons can be employed (which can go through 2-3 cm of steel). Thirdly, diffraction is phase specific. We only "see" the peak from one phase during the analysis. If peaks from all phases in a multi-phase object can be found, it is possible to determine the macro and micro stresses that exist in the irradiated layers. In the case of neutron diffraction, one can take advantage of the large penetration depth to analyze for macro and microstresses even in a single phase material. For example, if one irradiates the entire thickness of a shot-peened specimen, one "sees" the total macrostress gradient which, of course, yields zero macro stresses. Thus, one only obtains the microstress averaged over the thickness. If, then, one limits the diffraction volume at specific depths through the use of slits, one obtains the total (macro + micro) stress at the depths analyzed. The capability of separating macro and micro residual stresses in different phases is, so far, unique to diffraction methods. Another novel use of the material specific nature of diffraction is analysis of thin films and their substrates in-situ.

Diffraction techniques described above, and particularly the x-ray methods enjoy quite wide-spread usage in residual stress determination. Such analysis may be carried out in a diffraction laboratory, where small parts are routinely measured, in a factory where frequent inspection during manufacture is needed, or in the field, for example, at railyards, on aircraft carriers, oil-rigs or at power stations. In the laboratory, the tool of choice is usually the standard powder diffractometer, which can also be used for a multitude of other tasks. These machines are too bulky for most field applications, where, self-contained, portable x-ray stress analyzers are used. In figure 14, one such portable machine is shown. This and similar machines have enabled accurate on-site monitoring of residual stresses.

Future Trends in Stress Analysis

Despite all the advances in stress analysis, and the proven benefits in stress monitoring during service, these techniques are usually employed a-posteriori, that is after a failure, to explain why the failure occurred in the first place. In the past, when energy was plentiful and demands on structures smaller

than the current ones, the effects of residual stresses could be negated by over-design, i.e., by making the structures much stronger than needed. Nowadays, because of the current requirements for reliable energy and material efficient structures on the one hand, and the drive for the ever smaller components in the microelectronics industry on the other, residual stress associated failures are becoming more prevalent. Thus, existing techniques are enjoying more widespread use than before. However, to meet the needs of measuring stresses in smaller and smaller regions, new techniques and concepts are needed. Most of the stress concepts in use now are based on continuum mechanics. When we go down to current device sizes in the microelectronic circuits, the fundamental assumptions of continuum mechanics no longer hold. Other areas of interest include the stress as one gets closer and closer to the surface. The depth of x-ray penetration (20 micrometers or so for most metals), considered very shallow for traditional structures, is immense if one wants to analyze a film 200 Angstrom in thickness. Fundamental questions also remain; what is the stress of the first couple of layers of atoms next to the free surface? How does it differ from the bulk? These and other challenges on both the experimental and the theoretical sides promise to make stress analysis an exciting field for quite some time into the future.

Modern industrial usage of residual stresses is also growing. One example would be the new segmented mirror of the new W. M. Keck observatory on Mount Mauna Kea, Hawaii. The basic shape of the segments are achieved through the use of residual stresses (20). To give an off-axis section an asymetric shape, the mirror blank is first strained by the application of weights and levers around the edge. Then it is ground to curvature in this condition, while still under strain. Then the restraints are removed and the mirror warps into its basic shape due to residual stresses caused by the constrained grinding. We are making "magic" mirrors again!

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VITA

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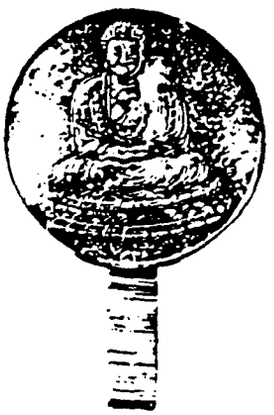
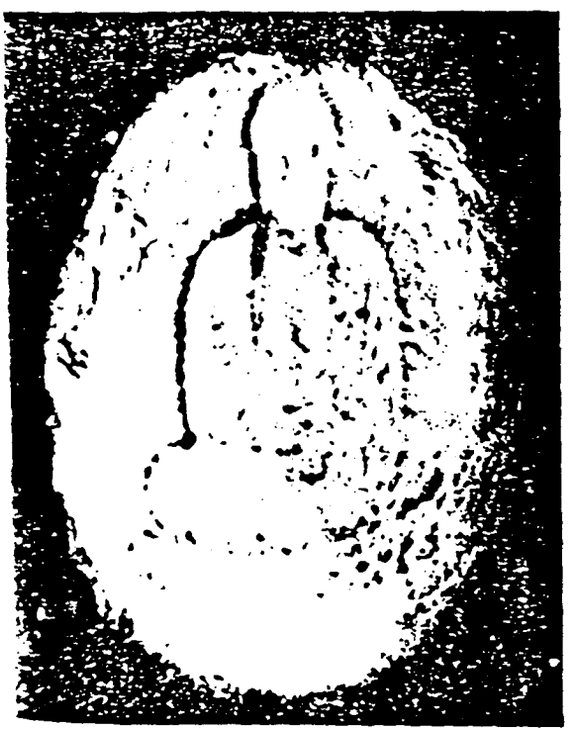


Magic mirror. Bronze. 19th century. Japan.
Stanford University Museum, gift of Jane L. Stanford

"Magic" mirror. Bronze. 19th century. Japan.
Stanford University Museum, gift of Jane L. Stanford
(The punch marks can be seen close to the threads).



Magic mirror, showing image reflected on a white surface.
Bronze. 19th century. Japan.
Stanford University Museum, gift of Jane L. Stanford

"Magic" mirror, showing image reflected from white surface back onto polished face of mirror.
Bronze. 19th century. Japan.
Stanford University Museum, gift of Jane L. Stanford

Figure 1: Chinese Magic Disk.

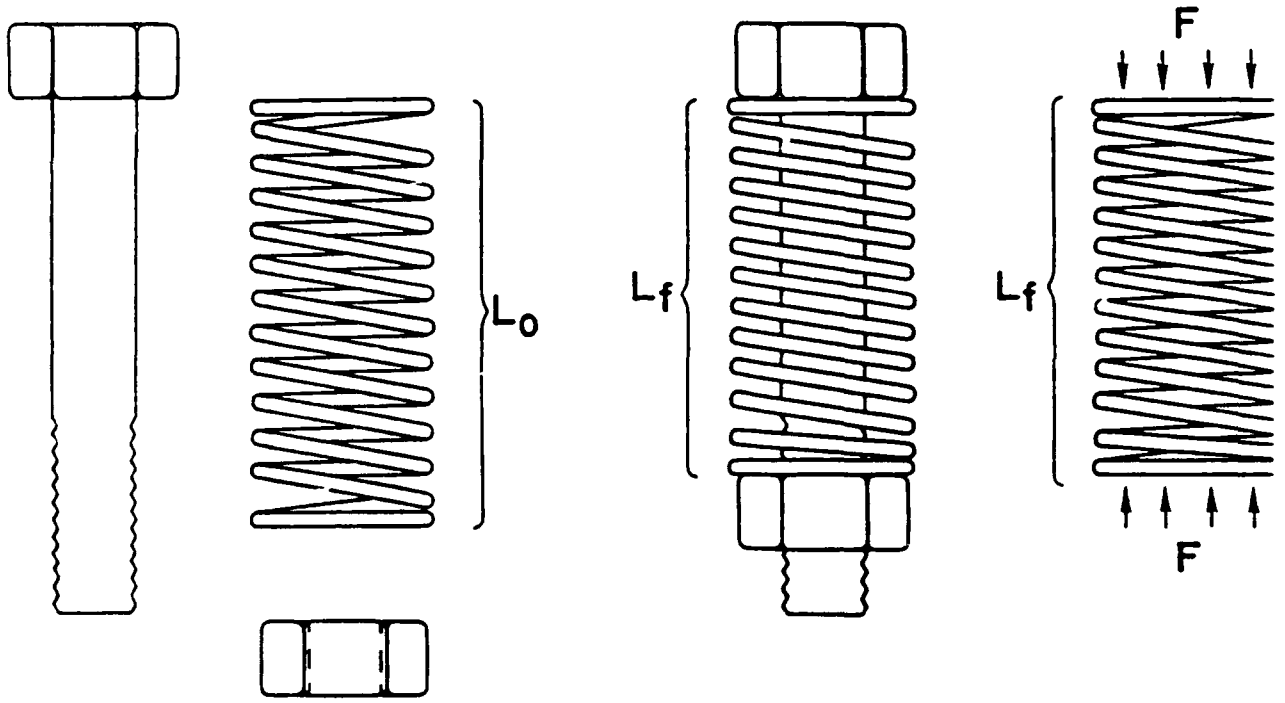


Figure 2: Residual stresses in a spring assembly. When the distance between the nut and the bolt is less than the rest length of the spring L_o, the spring will be placed in compression. The spring, in turn, will place the bolt-nut pair under tension.

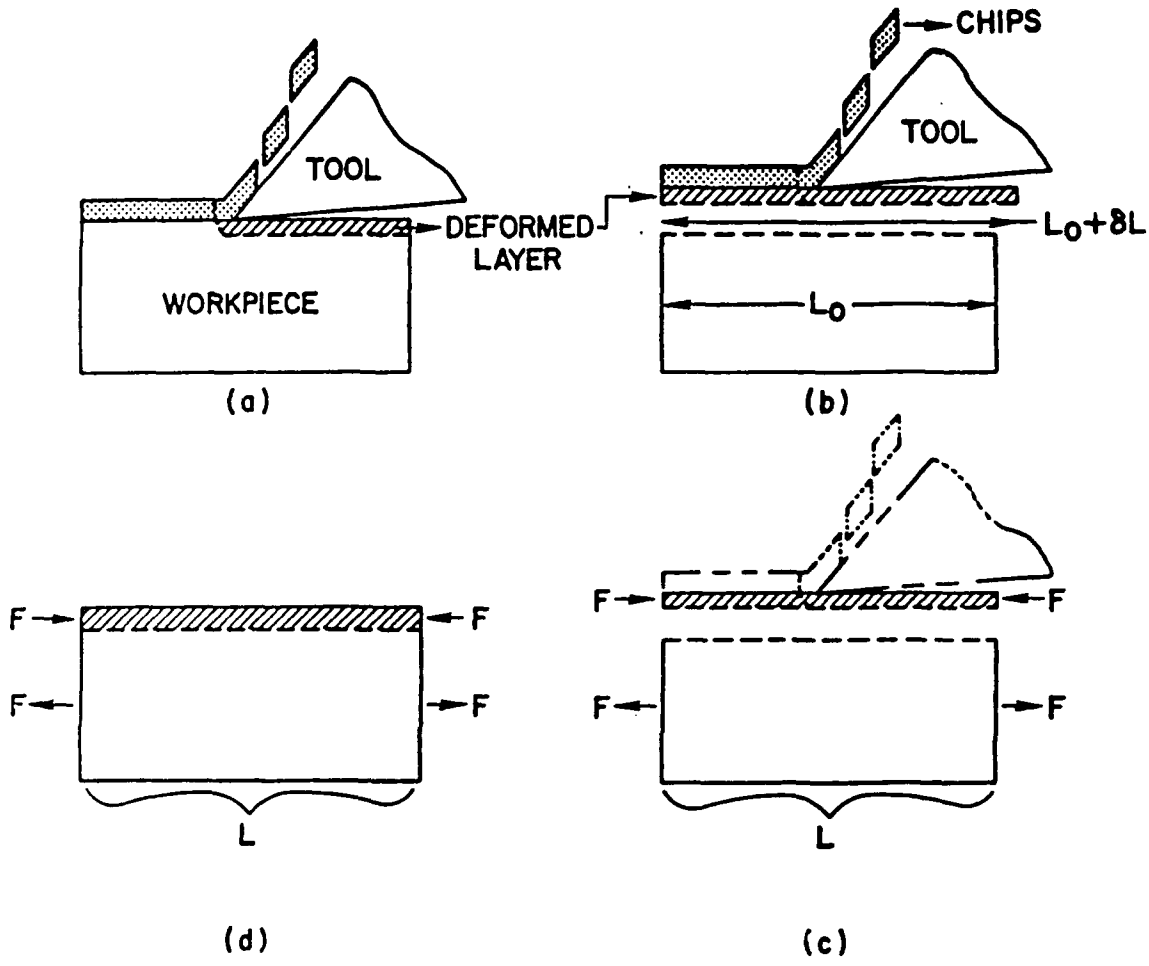


Figure 3: Schematic of stress formation during the machining operation. In this schematic, we assume that the surface is removed from the remaining material and machined separately. The tool causes permanent strains, and thus, a length change in the surface layers (b). To attach this elongated layer back on the bulk of the material, surface tractions must be applied to match the boundaries (c). After the interface between the surface and bulk is joined together and surface forces released, the system has residual stresses since the surface and bulk layers mutually constrain each other from achieving their stress-free dimensions (d).

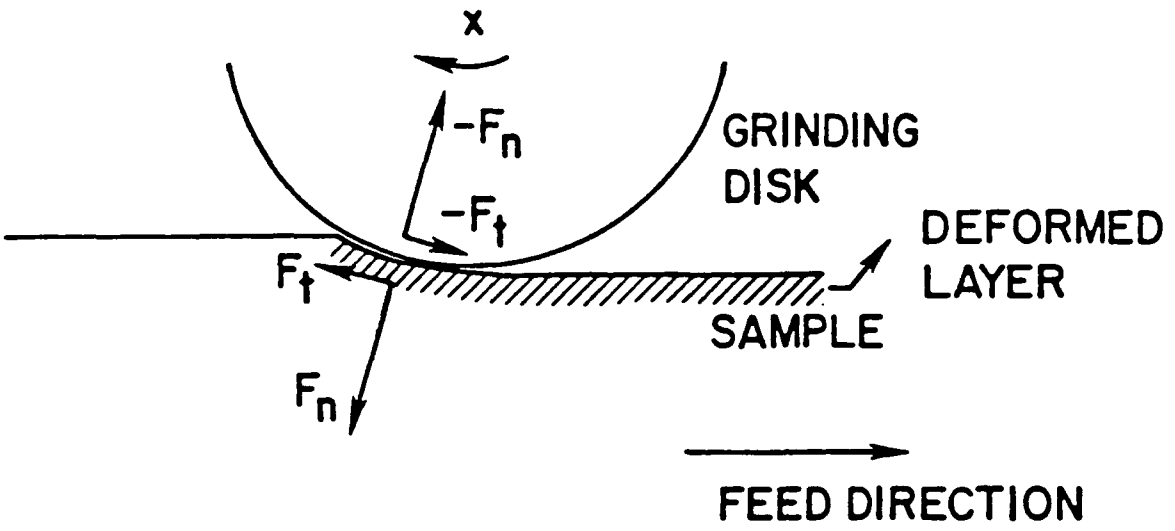


Figure 4: Schematic of the deformation and chip removal regions during the grinding operation and the cross section of the chip removed.

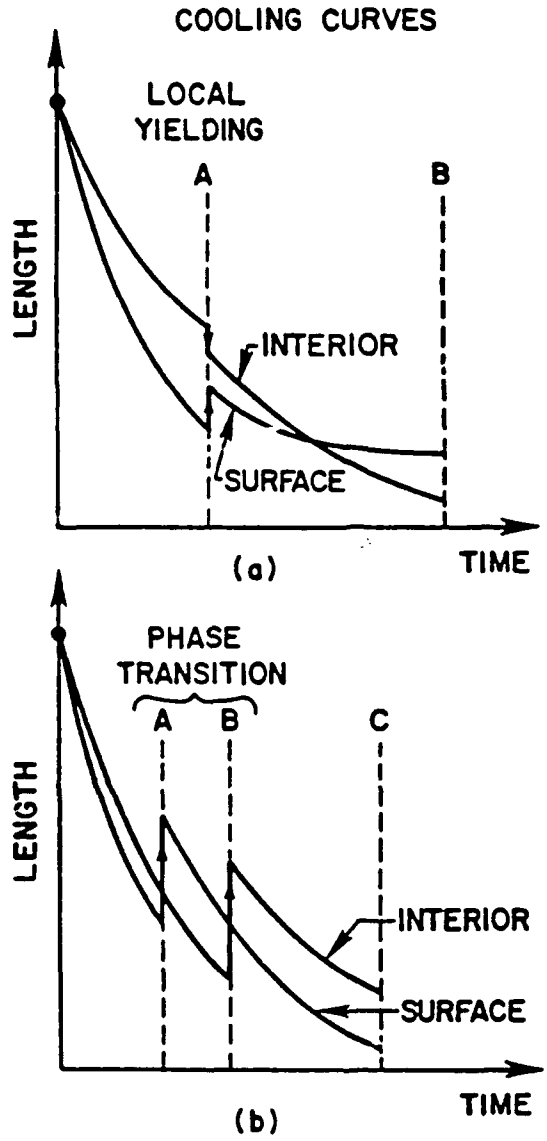


Figure 5: Variation of length in the interior and on the surface of an object undergoing heat treatment without phase transformation (a) and with transformation (b). The dimension and property changes associated with the phase transformation can completely reverse the residual stresses in the material.

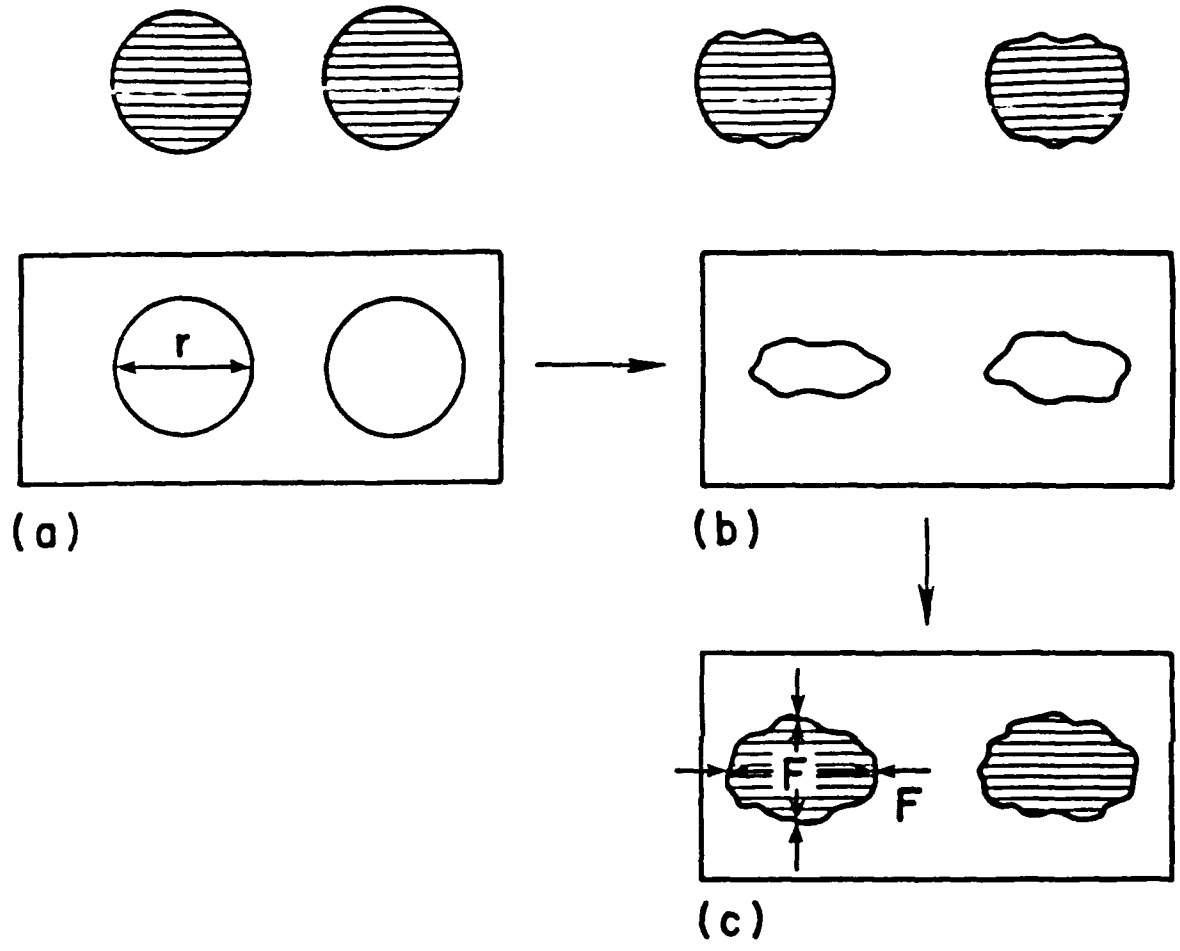


Figure 6: Formation of microstresses in a two-phase material. Here we assume that the matrix (bulk material) is weak and the second phase (shaded) is strong. If the second phase particles could have been removed from the material prior to any deformation, they would leave behind voids that exactly match their shape (a). If the matrix and precipitates are, then, separately subjected to the applied forces from the machining operation, they would deform differently, subject to their particular mechanical properties (b). To fit the second phase particles back into the cavities in the matrix, one would have to constrain the matrix and the second phase particles with a particular micro stress distribution (c).

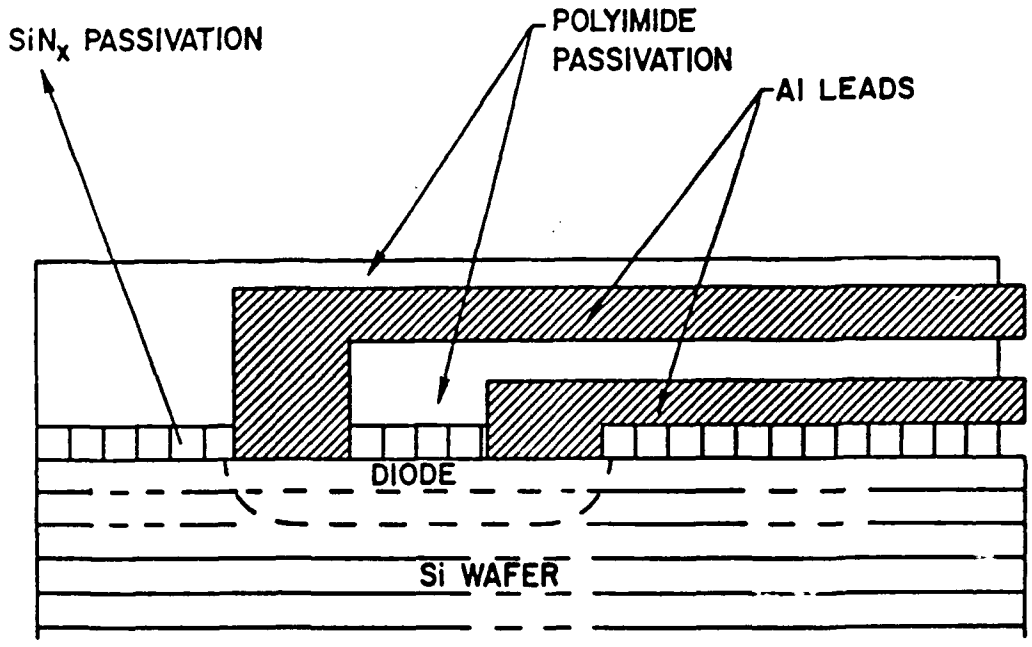


Figure 7: A simplified cross-section of a chip showing the metallization and passivation levels around a diode.

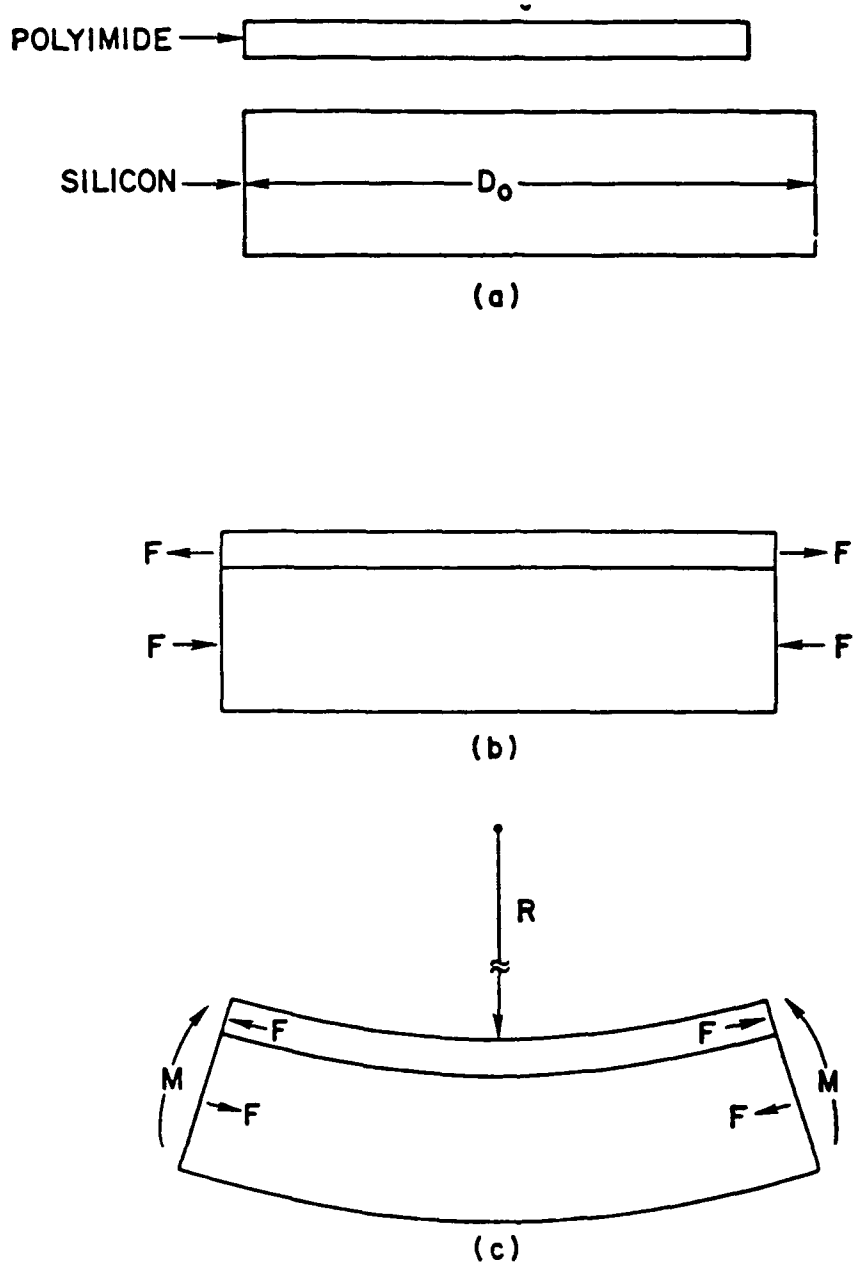


Figure 8: Formation of encapsulation stresses. The asymmetric distribution of forces around the middle of the silicon wafer cause finite moments M_1 which bend the coated wafer into a spherical shell section.

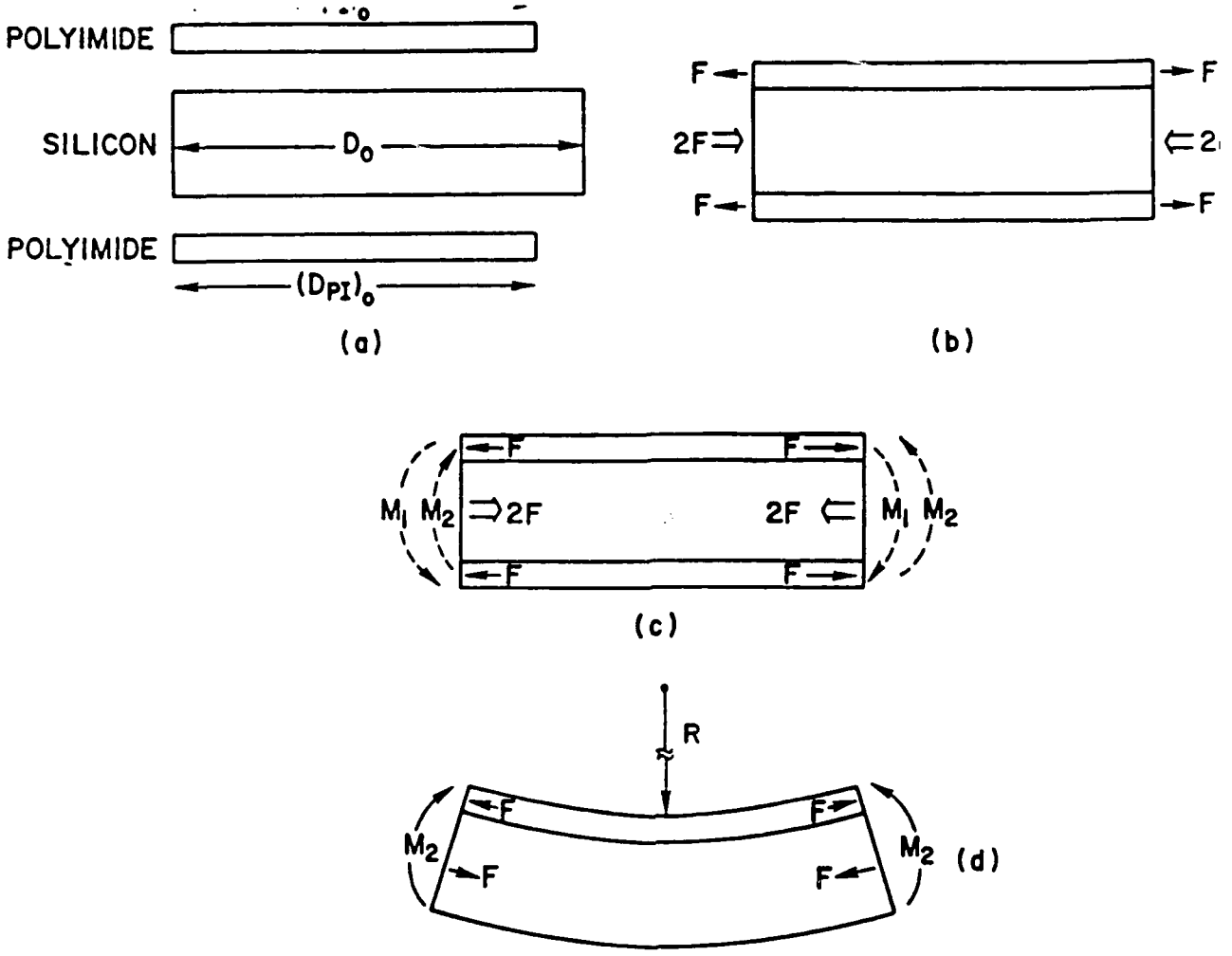


Figure 9: Double-sided encapsulation: In this case, the force distribution is symmetric around the center of the silicon and the coated wafer stays flat. However, the stress on the silicon is twice that of single sided encapsulation. If the polyimide on one side is etched away, the wafer again bends with the characteristic curvature of single-sided encapsulation (d).

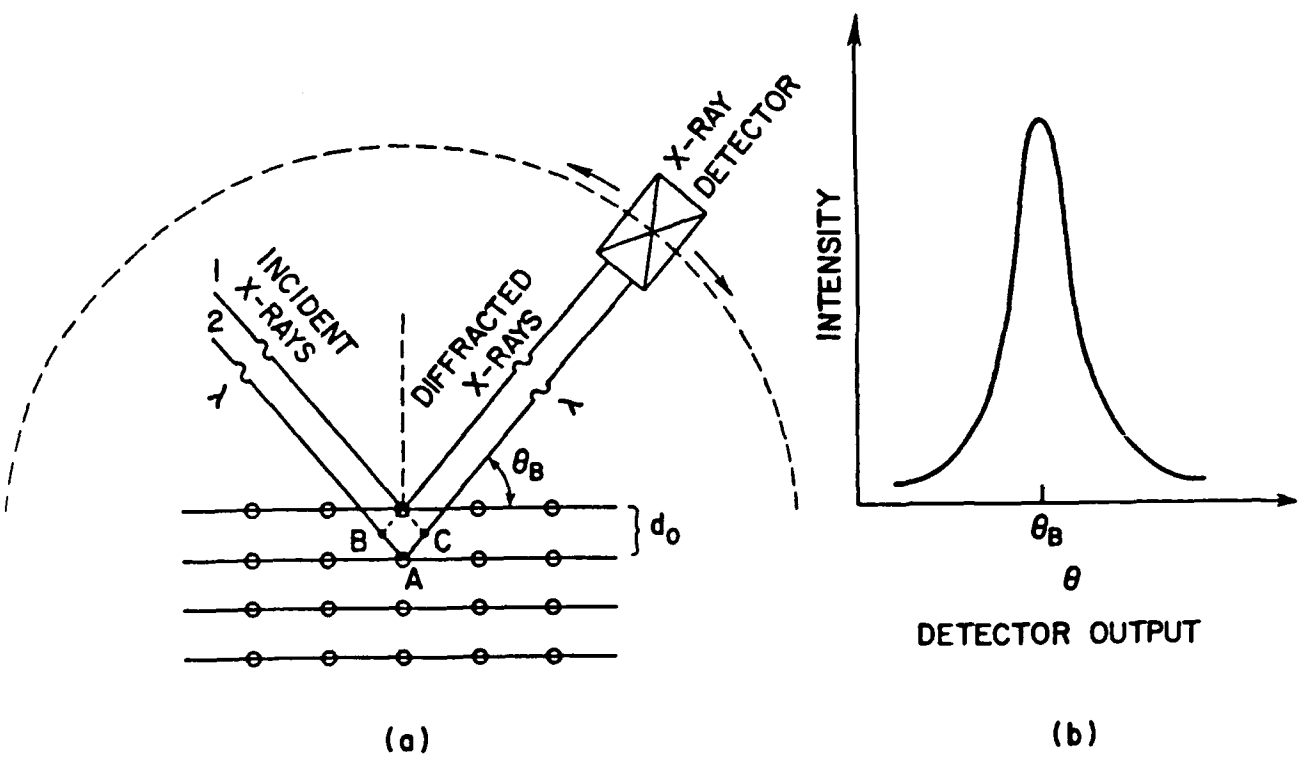


Figure 10: Diffraction of X-rays by a crystal (a). Constructive interference of the incident rays of wavelength λ occurs when the path difference between rays 1 and 2 from layers 1 and 2 are (BA+AC) is an integral multiple of λ. From trigonometry one can show that $BA=AC= d_0 \sin \theta_B$. Thus, diffraction occurs when $n\lambda = BA+AC = 2\, d_0 \sin \theta_B$. In figure (b) we show the variation of diffracted intensity with incidence angle observed by a detector.

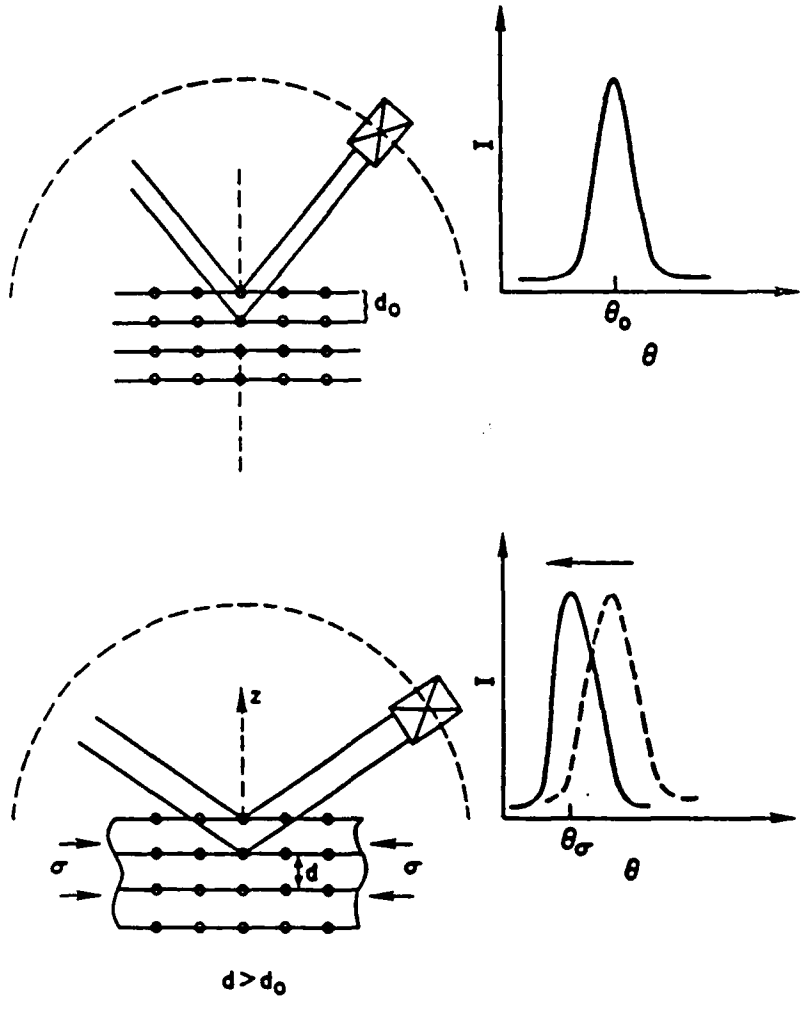


Figure 11: Variation of plane spacing (along the z direction) and the diffraction peak in response to an applied compressive stress along the x direction.

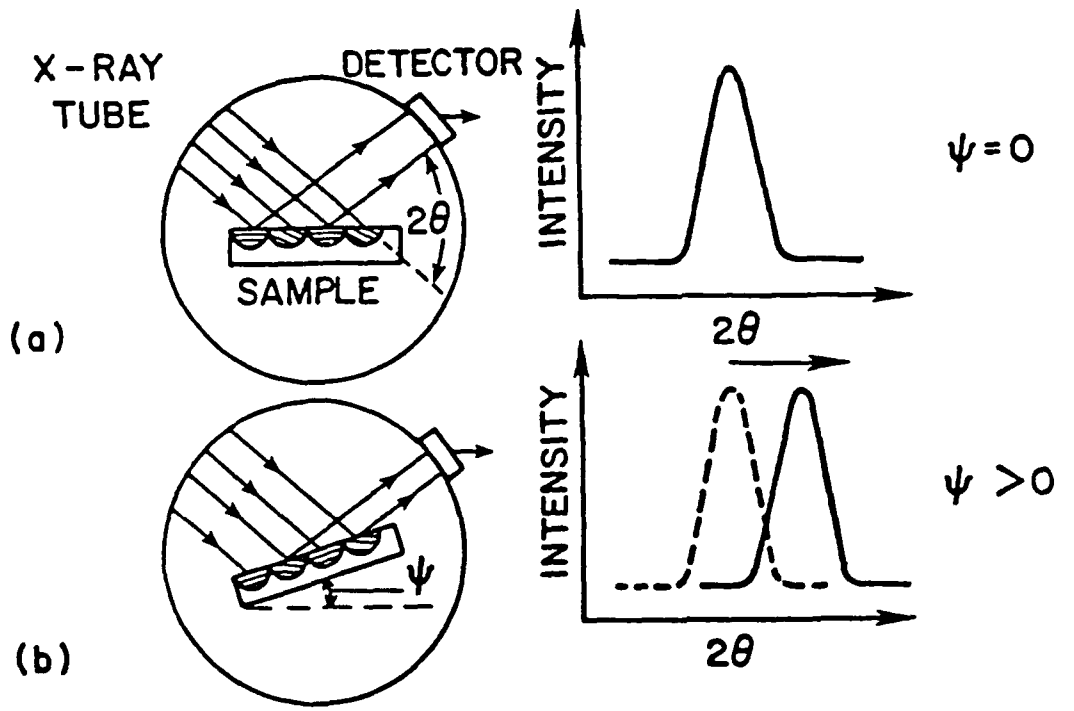


Figure 12: Diffraction from a powder sample during stress measurement. At each ψ tilt, different crystallites having different resolved stresses diffract, this is seen in the shift of the diffraction peak at each tilt.

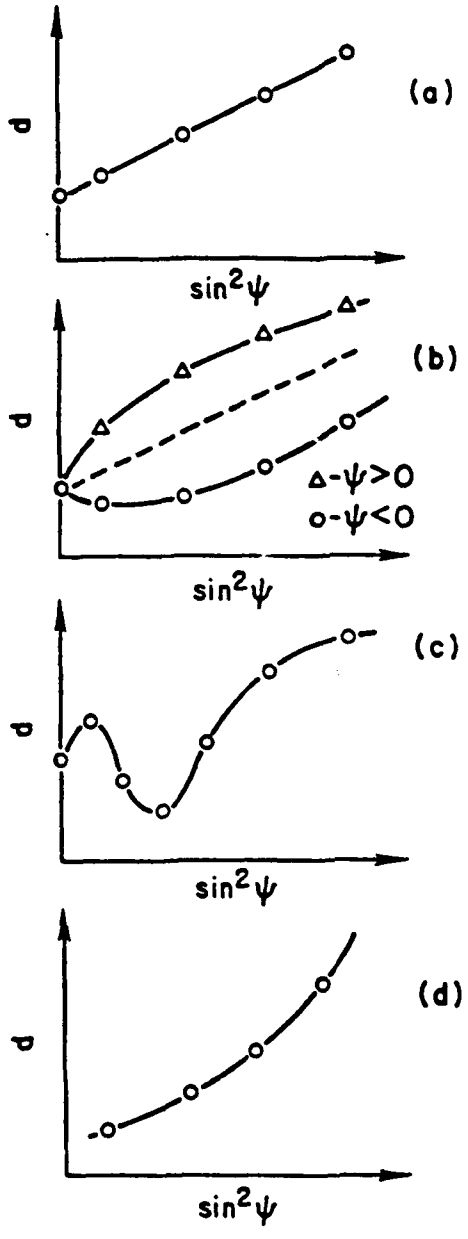


Figure 13: Lattice spacing versus "square of the sine of the tilt" observed during stress measurement. If experimentally obtained data is a straight line, the residual stress is most likely only in the plane of the surface. "Psi-split" data (b) indicates the presence of shear stresses along the surface normal. Curvature indicates large strain/stress gradients normal to the surface(c), while oscillatory data (d) indicates the presence of large inhomogeneous stress/strain variations in the surface.

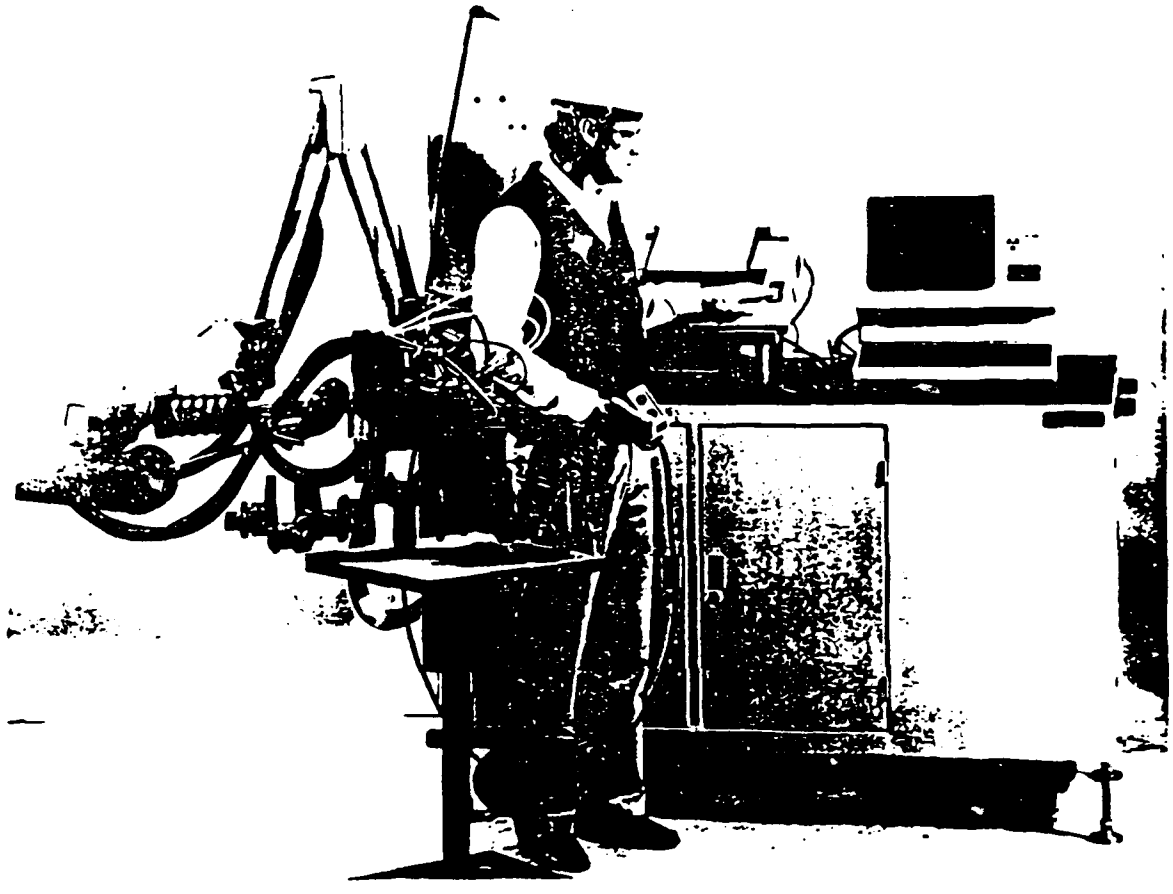


Figure 14: A portable x-ray stress analyzer. X-ray tube at left, detector at right. This instrument was co-invented by the authors. Reprinted with permission of Technology of Energy Corporation, Knoxville, TN.

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13 ABSTRACT

"Locked in" or residual stresses occur almost always in making and using materials, from computer chips and dental fillings to tanker hulls, pipe lines and air craft. These stresses can sometimes improve the life of a manufactured item, but can also lead to catastrophic failure.

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